Estimation of Dulling Rate and Bit Tooth Wear Using Drilling Parameters and the rock abrasiveness

Abstract: Numerous models have been suggested in the literature for predicting the time to pull the bit out to surface rather than predict or estimate the bit wear rate. Majority of the presented models failed to include all the drilling parameters such as the formation abrasiveness and bit hydraulic. In this paper, a new approach is proposed to improve the drill bit wear estimation that consists of a combination of both Bourgoyne and Young drilling rate model and the modified theory of variable weight and rotary speed. The presented technique enables estimation of the rock abrasiveness, and that lead to calculate the dynamic dulling rate of the bit while drilling to determine the dull grade of the bit. Based on achieved results and analysis of the wells, the dulling rate is proven to be a good indicator for predicting the bit wear compared with the mechanical specific energy.

Keywords: Rate of dulling, Bit wear, Mechanical specific energy, Rate of penetration,

1 Introduction

In oil and gas drilling attaining an optimum drilling conditions is key to reduce the cost of field development. It is difficult to assess and evaluate the efficiency of the drilling operation. In addition estimation of wear rate of drill bit is vital as identifying the right time for replacement could help saving significant operation cost. Two techniques have been reported in the literature to estimate the bit tooth wear. The first one is bit tooth flatness as a function of mechanical specific energy (MSE) (Abbas et al., 12-14 November 2014, Burgess and Lesso Jr, 1986) which does not take into account the formation abrasiveness and bit hydraulic. The second one is the approach based on combination of MSE and rate of penetration (ROP) model as presented by Rashidi et al. (2008) who assumed that the ROP is not affected by the change of mud weight.

The combined approaches considers the effects of bit tooth wear with other drilling factors, and it is mostly used in drilling e.g. model of Bourgoyne Jr and Young Jr (1974).

1.1 Bourgoyne and young drilling rate model

Many attempts were introduced in the literature to predict the ROP as a function of the variable drilling parameters (Kaiser, 2007). Recently; Rashidi et al. (2015) developed an ROP model based on the rock failure by a single insert for the perfect cleaning condition. However, all the stated approaches failed to consider the drilling factors that lead to accurate drilling rate prediction.

Bourgoyne Jr and Young Jr (1974) presented the most reliable model, which consist of eight coefficients that are calculated to estimate the ROP for roller cone bits as follows:

$$ROP = f_1 \times f_2 \times f_3 \times f_4 \times f_5 \times f_6 \times f_7 \times f_8 \quad (1)$$

The function equations are defined as follows:

$$f_1 = e^{2.303a_1} \quad (2)$$

f_1 is a function of formation drillability that is affected by bit type, formation hardness, and mud type, while a_1 is the model constant coefficient.

The functions of f_2 and f_3 are mainly related to the formation compaction.

$$f_2 = e^{2.303a_2(10000-TD)} \quad (3)$$

$$f_3 = e^{2.303a_3TD^{0.69}(g_p-9)} \quad (4)$$

Where TD is the true vertical depth in (ft), g_p is the pore pressure gradient in (lb/g), and a_2 a_3 are Bourgoyne and Young model constant coefficients.

The function of f_4 evaluates the overburden pressure on the rate of penetration.

$$f_4 = e^{2.303a_4TD(g_p-p_c)} \quad (5)$$

Where p_c is the mud density in (lb /g), and a_4 is the model constant coefficient.

Bourgoyne Jr and Young Jr (1974) stated that the relation between the overburden pressure and the rate of penetration could be represented by a straight line on semi log paper for range of overbalance that exist in the oil field. The coefficient a_4 is replacing the combination of constants (- 0.052 m), where m is the slope of the line.

f_5 is the function that takes into account the effect of diameter and weight of the bit on drilling rate.

$$f_5 = \left(\frac{\frac{W}{d_b} - (\frac{W}{d_b})_t}{4 - (\frac{W}{d_b})_t}\right)^{a_5} \quad (6)$$

Where W is the weight on bit in (klbs), d_b is the bit diameter in (ft), $\left(\frac{W}{d_b}\right)_t$ is the threshold weight on bit per bit diameter, and a_5 is the model constant coefficient.

Function of f_6 expresses on penetration rate RPM.

$$f_6 = \left(\frac{N}{60}\right)^{a_6} \tag{7}$$

Where N is the rotary speed in (rpm), and a_6 is the model constant coefficient.

The a_5 and a_6 coefficients were assumed by using experimental data obtained at moderate values of weight on bit WOB and rotation per minute RPM, a_5 usually is observed to be closer to a value of 1.0 and less than 2.0.

f_7 is the function that introduces bit tooth wear. It is suggested that a_7 is determined based on known efficiency of similar roller cone bit in offset well (Bourgoyne et al., 1986).

$$f_7 = e^{-a_7 h} \tag{8}$$

Where h is the fractional bit tooth wear, and a_7 is the model constant coefficient.

The a_7 coefficient for is recommended to equal 0.5 for wear of milled tooth bits, while for insert bits the coefficient may reach a value of 1.5.

The f_8 represent the relationship between the bit hydraulic and ROP.

$$f_8 = \left(\frac{F_j}{1000}\right)^{a_8} \tag{9}$$

Where F_J is the jet impact force in (lbs), and a_8 is the model constant coefficient.

The constant coefficients a_1 to a_8 have to be estimated for a certain type of formation in order to predict the drilling rate. The model of Bourgoyne and Young has a bounds for every coefficient obtained for different types of formation which are given in Table 1.

Table 1 Bourgoyne and Young Recommended bounds for each coefficient

Coefficient	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
Lower Bound	0.5	1E-06	1E-06	1E-06	0.5	0.4	0.3	0.3
Upper Bound	1.9	5E-04	9E-04	1E-04	2	1	1.5	0.6

2 Background

Drill bit reaches a point that becomes ineffective to continue drilling, hence the bit has to be replaced. However, this will require a trip to surface as a function of time and cost especially in offshore wells (Holbrook and Mittal, 1994). Therefore, it is very important to adjust the drilling parameters to avoid unnecessary round tripping of the drilling string (Gray and Cambridge, 1988). Most of the common methods that are currently used to predict the bit wear are based on the assumption that formation which is planned to be drilled is similar to that experienced in offset wells. Furthermore, there is no dynamic estimation of bit wear based on formation abrasiveness. Wear is usually expressed as a function of drilling parameters (Holbrook and Mittal, 1994). This was confirmed by Moran (2006) who also reported that the rate at which the bit start wearing is mainly related to ROP.

Waughman et al. (2002) stated that in order to estimate the bit wear from drilling data, a better understanding of how drilling parameters is affecting the bit life had to be gained. They added that a number of techniques existed but failed to capture and consider all drilling factors. It should be noted that by combination of (Bourgoyne Jr and Young Jr, 1974) and (Galle and Woods, 1960) models all drilling parameters can be considered, and this will be addressed in this paper.

Galle and Woods (1960) developed a method to determine the best variable combination of both WOB and RPM to reduce the cost of drilling operation. Sharing the same aim, Edwards (1964) included the impacts of bit hydraulic and bit life condition (see Equation 12).

In this paper, a new technique employing ROP, WOB, RPM, and MSE measurements is introduced to study the relationships, and how these parameters affect the dulling rate and bit condition. To perform the analysis, the data collected from offset wells are used to derive a new equation to account for a combination of drilling parameters. Based on the work of Galle and Woods (1960), the drilling rate as a function of bit wear can be expressed as follows:

$$ROP \ \alpha \ \left(\frac{K}{(0.928 * D^2) + (6 * D) + 1.0}\right)^a \tag{10}$$

While Bourgoyne Jr and Young Jr (1974) stated a different correlation of the drilling rate with the bit wear:

$$ROP \ \alpha \ K(e^{-a.DG}) \tag{11}$$

Where K is 1.0 (for all formations except very soft formations), D is the fractional tooth grades (height), DG is the fractional tooth wear, and a is an exponential fit based on the field data.

It is difficult to estimate the rate of dulling of a rock bit as the teeth in different rows are not subjected to wear at the same rate. However, Galle and Woods (1960) introduced an equation to determine the rate of dulling as a function of the basic drilling parameters as follows:

$$\frac{\delta d}{\delta t} = \frac{1}{A_f} * \frac{i}{a * m} \tag{12}$$

$$i = N + (4.348 * 10^{-5} * N^3) \tag{13}$$

$$m = 1{,}359.1 - (714.19 * \ log_{10} * \ W) \tag{14}$$

$$a = (0.928 * D^2) + (6 * D) + 1.0 \tag{15}$$

Where i is a function of rotary speed, a is representative condition of bit life, D is the fractional grade, m is a quantity as a function of weight on bit, and A_f expresses the formation abrasiveness.

Note i increases with rotary speed, m decreases with an increase in weight on bit and a increases with bit wear. As a result, the rate of dulling decreases as grade increases. Thus, the dulling rate in Equation 12 express the original tooth height remaining at any dull condition.

Fractional grade is suggested to increase linearly with depth as proposed by Rashidi et al. (2008) as follows:

$$D = ((d_{cur} - d_{in})/(d_{out} - d_{in})).(DG/8) \quad (16)$$

Where, d_{cur} is the current depth (ft), d_{in} is the depth-in (ft), d_{out} is the depth-out (ft), and DG is the actual tooth height worn away which is measured when the bit is pulled out of hole, and it ranges between zero to eight; zero is reflecting the new condition and eight representing the completely worn out tooth.

Taking into account both considerations as mentioned in Equations 10 and 11, and as it is clear that the bit wear is inversely proportional to the penetration rate, Equation 15 is modified in this paper as follows:

$$a = ((0.928 * D^2) + (6 * D) + 1.0)^{a_7} \quad (17)$$

Where a_7 is a model constant coefficient as described in Equation 8.

In Equation 12, the effect of bit type, bit hydraulic, and formation are all included in the abrasiveness constant A_f, which used to be calculated by an Equation as a function of parameters obtained from graphs as provided by Galle and Woods (1960). The graphs were created based on the type of formation being drilled; i.e. very soft, soft-medium or medium-hard.

In this methodology, a new equation is introduced to estimate the abrasiveness constant, keeping the same factors that considered in the approach of Galle and Woods (1960). The abrasiveness constant can be determined as follows:

$$A_f = f_1 * f_8 \quad (18)$$

Where f_1 and f_8 are expressed as the formation drillability, bit type and hydraulic as introduced in Equations 2 and 9.

Some data are unknown and must be calculated, this goes into the determination of the jet impact force using the following equations (Bourgoyne et al., 1986):

$$F_J = p_c * R * j / 1932 \quad (19)$$

$$j = 0.321 * R / TFA \quad (20)$$

Where p_c is the mud density in (lb_m/g), R is flow rate in (gal/min), TFA is jet total flow area in (sq.in), and j is jet hydraulic in (lb_f).

Based on the study done by Pessier and Fear (1992), it was reported that the value of bit coefficient of friction μ ranges between 0.21 and 0.84 for both roller cone and PDC bits, respectively. Therefore, as all tested bits are roller cone bits, μ is assumed to be equal to 0.24.

(Ghosh et al., 2015, Teale, 1965) defined the mechanical specific energy as the energy needed to remove one unit of rock. MSE provide an instantaneous indication of drilling efficiency as it does not consider the bit wear effect into account. Dupriest et al. (2005) stated that one of the main objectives to optimize the ROP is the analysis of MSE in the real time.

MSE values were determined by applying Equation 21, (Rabia, 1985):

$$MSE = W * \left(\frac{1}{A_{bit}} + \frac{13.33 * \mu * N}{d * ROP}\right) \tag{21}$$

Where W is the weigh on bit in (lb), d is the bit diameter in (inch), N is the rotary speed in (rpm), A_{bit} is the bit area in (sq.in), and ROP is the rate of penetration in (ft/hr).

Bit records can only show the efficiency of the bit and how the bit perform along the interval. Mud logs on the other hand, gives an indication how the bit penetrate as a function of drilling parameters (Mason, 1987). The variation of ROP with WOB and RPM are measured from mud logging data recorded at every five feet till reach the depth when the bit pulled out of hole where drilling rate is estimated as an average ROP for the whole interval.

Edwards (1964) reported that bit becomes ineffective if ROP drops, as the cost per foot will be increased. The bit life as ROP is decreased relies on the rock properties, bit type, and mud hydraulic. Accordingly, the basic theory of this work recognizes that the bit wear is a function of drilling parameters, which include the rock abrasiveness and the mud effect.

The bit wear is expressed just at the total depth; thus, only data at the final depth is used to estimate the bit wear as shown in Tables 6, 8, 10, 12 and 14. According to the geometry of the bit teeth, it is clear to say that it will require longer to wear out the last increment of the tooth height comparing with the time will be taken for the first increment for the same tooth. This phenomena was expressed by Edwards (1964) to develop an equation to estimate the wear function $f(D)$:

$$f(D) = 8 - (7 * D) \tag{22}$$

Equation 22 was obtained by assuming that the bit is worn with $\frac{1}{16}$ wear in the inner row teeth when the new has a tooth width of $\frac{8}{16}$.

In this work, Equation 22 is developed to be expressed as a function of dulling rate as given in Equation 23:

$$f(D) = 8 - (8 * D * \Delta D) \tag{23}$$

Where ΔD can be determined as follows:

$$\Delta D = \frac{\delta d}{\delta t} * T \tag{24}$$

$$T = (d_{cur} - d_{in})/ROP \tag{25}$$

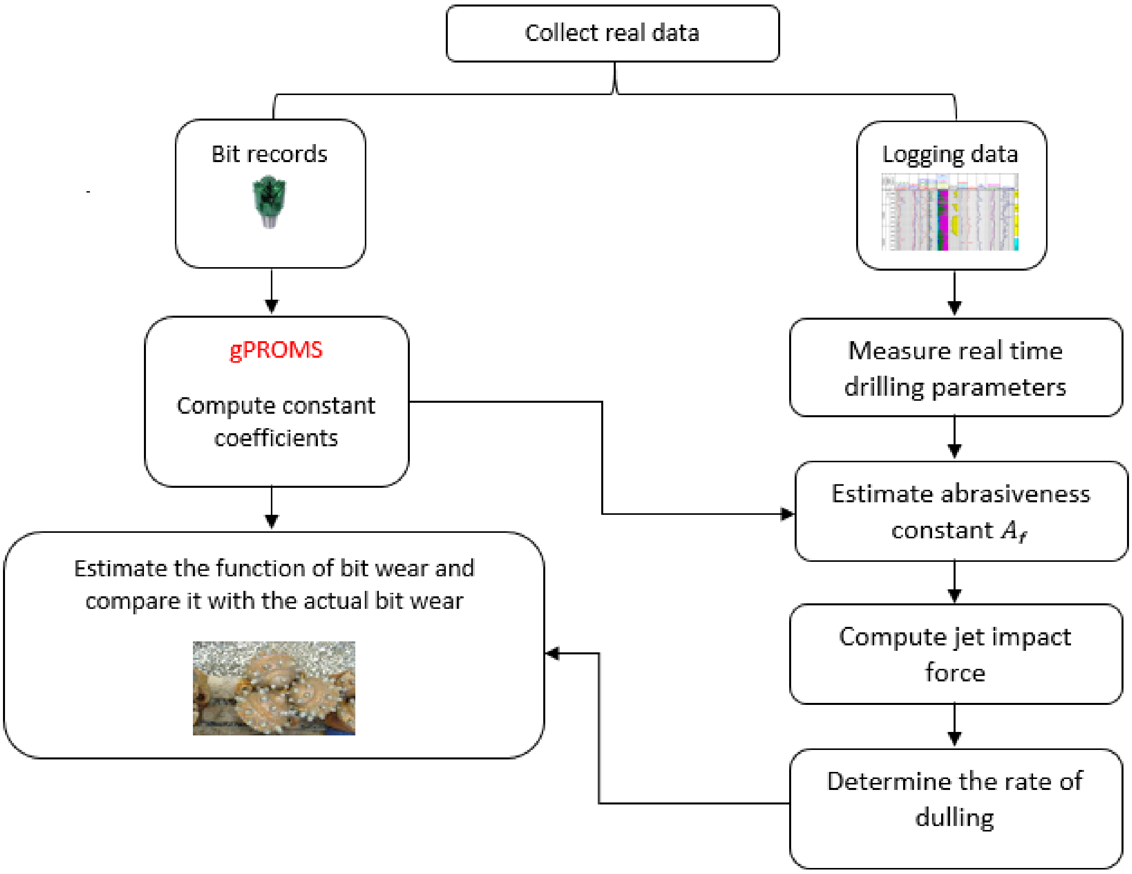
Where values of $(8 * D * \Delta D)$ are equivalent to the original tooth height remaining at any dull condition, and T is the drilling time in (hours).

The validity of the technique is demonstrated with real data from the existing fields in Libya. Five vertical wells in two different fields have been used in the further calculations to validate the approach. In this approach effect of bearing failure is neglected. Variable data such as weight on bit, rotary speed, and rate of penetration are being used for the further calculations to determine the tooth wear for every well. The overall methodology is shown in the flow chart given in Figure 1.

The jet impact force can be computed by applying Equation 19, and jet hydraulic can be determined using Equation 20 as a function of flow rate and the jet total flow area. In this methodology, the abrasiveness constant A_f can be estimated using Equation 18.

The second part of the calculations is to determine the mechanical specific energy which produce the Figures 4, 6, 8, 10, and 12 by using Equation 21 and assuming that the bit coefficient of friction μ is equal to 0.24. Next, the bit dulling rate is determined at every five feet along the 12.25 section using the Equation 13. Finally, the bit tooth wear can be estimated by applying the Equation 23.

Figure 1 Flow chart illustrating the proposed technique



2.1 **Determination of constant coefficients of BY model using gPROMS**

gPROMS (Version 4.2.0) was used to estimate the parameters using its parameters estimation tool to calculate the Bourgoyne and Young model (BY) coefficients. The data collected from several wells within similar formation in two different fields were used for this purpose. The software set with $a_1 to\ a_8$ lower and upper bounds and run for 169 to 280 optimization iterations to show values with respect to the 95% confidence intervals.

In each formation, six experiment stages were built in the gPROMS parameter estimation. gPROMS applies a mathematical solver that is run as follows:

- Set the Bourgoyne and Young bounds that recommended for each constant coefficient, i.e. the upper bound, the lower bound, and the initial guess.
- For every set of values within every experiment stage, data inputs have to be assigned as fixed values (D, d_b , g_p , p_c, W , N , $\left(\frac{W}{d_b}\right)_t$, F_J , and h).

- The model equations can be applied to optimize the parameters and predict the ROP at every stage within the experiment bounds trying to minimize the error using the Sum of Square Errors (SSE), given in Equation 26.

$$SSE = \sum_{i=1}^{N_{data}} \left[\left(ROP_i^{Exp} - ROP_i^{Cal}\right)\right]^2 \qquad (25)$$

Where Exp and Cal are abbreviation of experiments and calculation, respectively.

In order to obtain accurate predicted rate of penetration and bit wear, the methodology is based on the following assumptions that set as a function of collected data from every bit used in the offset wells:

- Only applications with new and equivalent 12 ¼ bits are considered.
- Formation drillability is kept constant to study the WOB and RPM.
- The wear occurred to the inner row is evaluated, where the teeth is contacting the bottom of hole, and usually the inner row received the most wear (Edwards, 1964).
- The run should be within particular type of formation, and the wear is estimated only when the bit is pulled out of the hole.
- The reason for pulling the bit out of hole has to be related to the rate of penetration such as formation TD changes, hours on bit, etc. Reasons that are not related to the drilling rate such as pump pressure, torque, twist off, and left in the hole, etc., should not be considered.
- The mud used is water base and its density is ranging from 8.8 to 9.2 lb/gal along all wells. It is assumed the pore pressure is within 0.2 lb/gal as overburden due to lack of data in some wells.

3 **Results and Discussions**

3.1 **Field A**

The candidate formation in this field is Gir formation between the depths of 760 ft till 2668 ft, consist of Anhydrite and Dolomite. The formation is selected due to the drilling time for 12 ¼" section, where roller cone bits are subject of tooth wear while drilling.

3.2 **Field B**

Gata formations is tested where mainly limestone with anhydrite exists between the depths of 3080 ft to almost 8000ft.

The data from six vertical wells with 12 ¼" roller cone bits run were collected form Gir and Facha formations in the fields A and B, respectively. Six stages were created in the model for each field, and every stage is fitted with a certain real data that belong to a certain well as shown in Tables 2 and 3. The suggested bounds are considered and set to run the model. GPE software was used to compute the constant coefficients. Table 4 illustrates the values of the eight coefficients in both formations.

Table 2 Data obtained from wells at Field A

Well No	$Depth$ (ft)	ROP (ft/hr)	W (1000 lb)	N (rev/min)	h %	F_J (lbf)	Reason Pulled
Well A	2308	14.9	45	130	0.375	124	Hole Problem
Well B	1640	14.23	20	95	0.125	360	Hours
Well C	2132	13.7	35	110	0.625	904	Penetration Rate
Well D	2460	19.02	25	120	0.25	742	Hours
Well E	2150	26.6	45	125	0.375	856	Hole Problem
Well F	2451	18.1	30	100	0.25	978	Penetration Rate

Table 3 Data obtained from wells at Field B

Well No	$Depth$ (ft)	ROP (ft/hr)	W (1000 lb)	N (rev/min)	h %	F_J (lbf)	Reason Pulled
Well A	6606	32.1	35	130	0.25	1060	Core Point
Well B	4950	32.9	35	120	0.25	683	Hours
Well C	3965	25.5	30	120	0.0	935	Hole Problem
Well D	4293	18.2	30	120	0.0	697	Bottomhole Assembly
Well E	7000	17.9	35	100	0.125	810	Hours

Table 4 Estimated constant coefficients using GPE

Formation	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
GIR	0.7451	1.05E-04	0.0009	3E-06	0.612	0.772	0.906	0.417
FACHA	0.846	1.99E-04	1.20E-04	6.79E-06	1.95	0.98	0.62	0.58

Figures 2 and 3 show the predicted values of ROP obtained from gPROMS and actual penetration rates against the total depth for the both formations. The Predicted Residual Error used by (Tarpey, 2000) is determined for prediction of ROP as follows:

$$PRE = \frac{\left[\sum_{i=n}^{n\,data}\left(ROP_{act} - ROP_{pre}\right)^2\right]^{1/2}}{n} \tag{26}$$

Where n is the number of stages. Only 1.4 % errors is observed by applying the GPE model in the field A while 8.3 % is the estimated error for the difference between actual and predicted ROP in the field B.

Figure 2 Comparing actual and predicted penetration rate for Gir formation

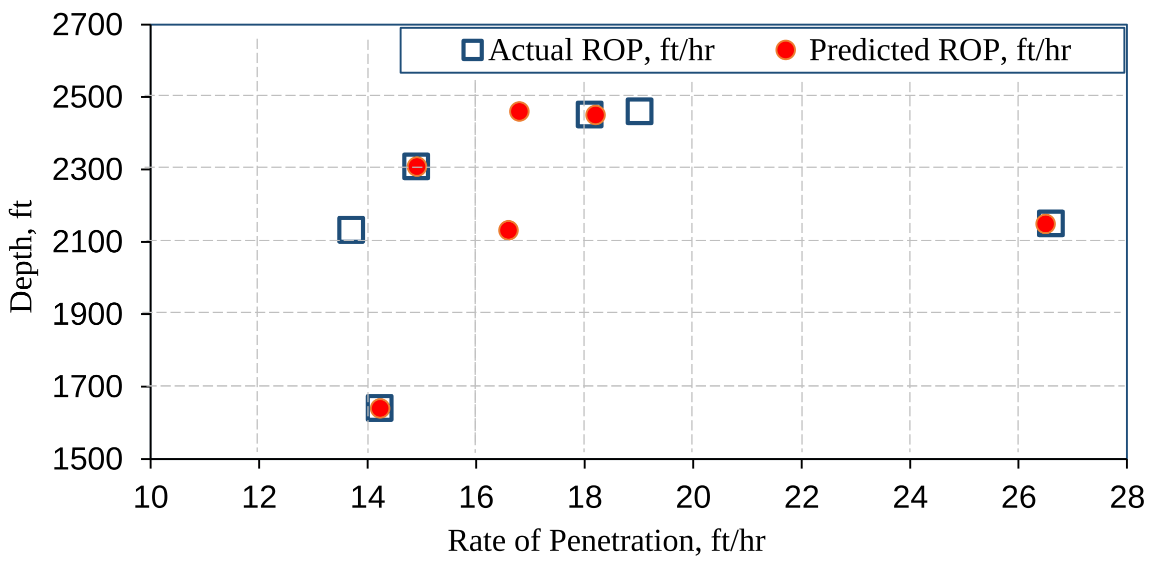
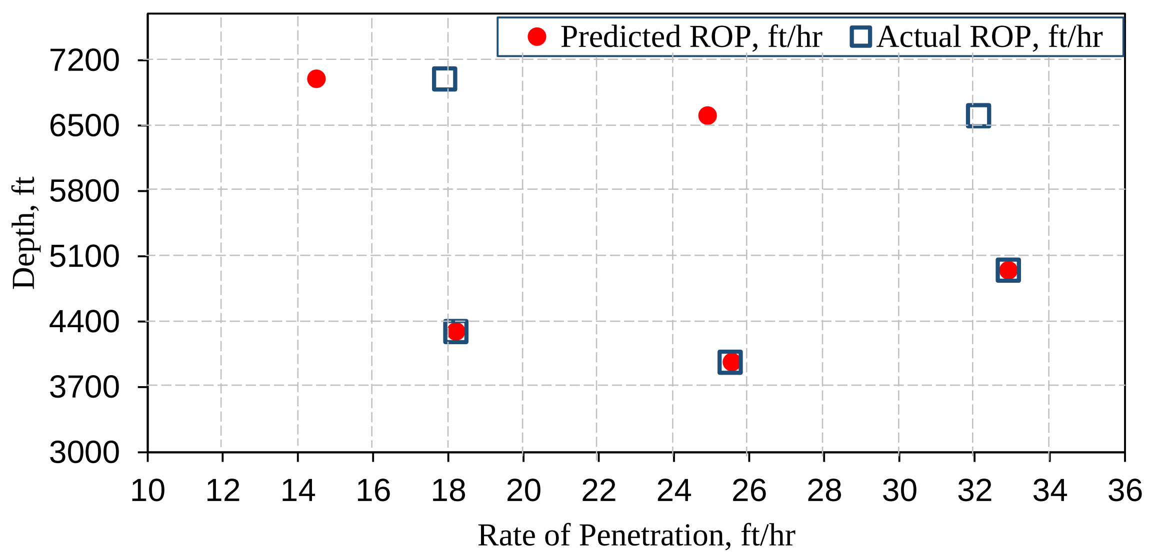


Figure 3 Comparing actual and predicted penetration rate for Gata formation

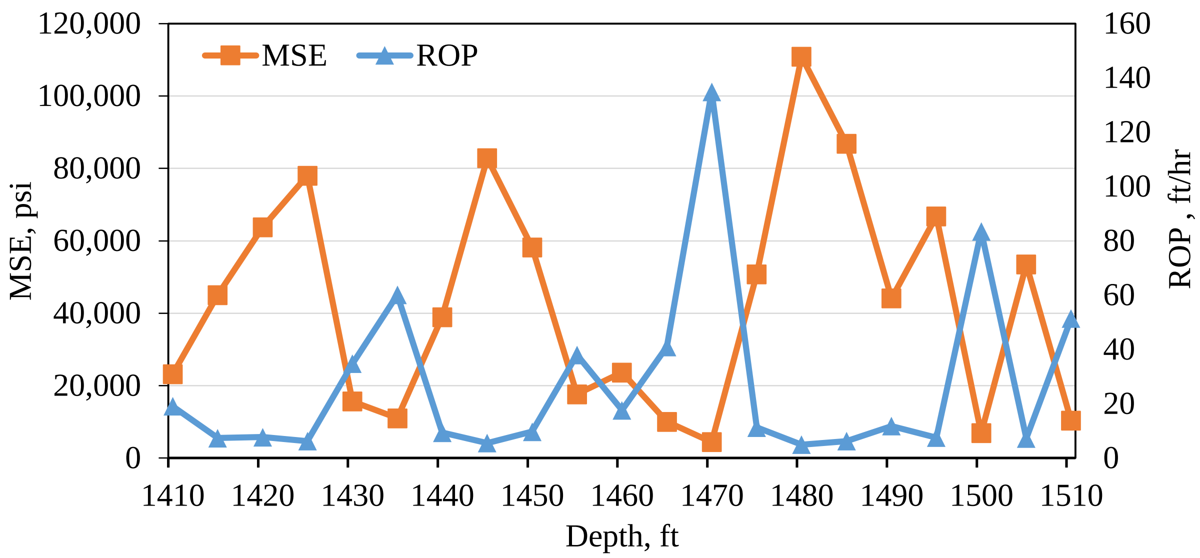


4 **Tooth bit wear estimation**

4.1 **Well 1**

Well 1 is located in field A. A 12 ¼" roller cone bit started drilling at a depth of 1264 ft to 2772 ft, at which point it was pulled out because of decreasing penetration rate. The bit drilled almost 100 ft in different formations. The calculated parameters are listed in Table 5, with graphs more focused on highlighting the change in drilling parameters of 100 ft interval, starting from 1410 ft to 1510 ft as shown in Figures 4 and 5.

Figure 4 MSE & ROP vs. depht in well 1



It is noticeable from Figure 4 that MSE reacted inversely with ROP. Low ROP leads to more energy required to penetrate the formation due to factors such as WOB, RPM, hole-cleaning condition, and the condition of the bit, or a combination of all. The sudden increase of ROP at 1470 ft was because the bit entered in the high-pressure zone. The pore pressure was 8.6 lb/gal at 1460 ft depth and recorded 12.5 lb/gal at 1470 ft. Figure 5 (a,b,c,d) shows the variations between each of the following variables: dulling rate, WOB, RPM and ROP, and the depth. At almost constant RPM of 90 r/min till depth of 1465 ft, the dulling rate was increasing with WOB as ROP increases as shown in Figure 5 (b,c,d). However, when the RPM is changed from 83.4 to 111.6 r/min, the dulling rate jumped up from 0.055 to 0.09, which indicates that the bit become more efficient, and accordingly, the ROP increased more than three times.

Table 5 Mud log data recorded within interval of 100 ft – Well 1

Depth (ft)	ROP (ft/hr)	WOB (klbs)	RPM (r/min)	Flow (gal/min)	TFA (sq.in)	j (lb_f)	Fj (lbs)	F1 (--)	F8 (--)	a (--)	m (--)	i (--)	D (--)	$\frac{\delta d}{\delta t}$ (- /hr)	MSE (psi)
1410	19.11	19	88.6	365	0.45	260	438	5.589	0.707	1.07	445.8	118.8	0.0121	0.0633	23171.806
1415	7.366	14.2	89.2	365	0.45	260	438	5.589	0.707	1.07	536.1	120.1	0.0125	0.0531	45029.227
1420	7.732	19.6	96	365	0.45	260	438	5.589	0.707	1.07	436.2	134.5	0.0129	0.0729	63723.689
1425	6.288	19.6	95.6	365	0.45	260	438	5.589	0.707	1.07	436.2	133.6	0.0133	0.0723	77989.288
1430	34.81	26.2	78.6	365	0.45	260	438	5.589	0.707	1.07	346.2	99.71	0.0138	0.0679	15671.909
1435	60.14	27.6	90	365	0.45	260	438	5.589	0.707	1.08	330	121.7	0.0142	0.0867	11020.337
1440	9.405	15.2	92	365	0.45	260	438	5.589	0.707	1.08	515	125.9	0.0146	0.0573	38960.063
1445	5.57	19.2	91.8	365	0.45	260	438	5.589	0.707	1.08	442.6	125.4	0.0150	0.0664	82809.886
1450	9.751	23.6	91.8	365	0.45	260	438	5.589	0.707	1.08	378.6	125.4	0.0154	0.0774	58224.62
1455	38.02	27.6	91.8	365	0.45	260	438	5.589	0.707	1.09	330	125.4	0.0158	0.0886	17636.843
1460	17.66	18.8	84.6	364	0.45	259	434	5.589	0.704	1.09	449.1	110.9	0.0162	0.0577	23677.755
1465	40.95	18.6	83.4	367	0.45	261	441	5.589	0.71	1.09	452.4	108.6	0.0167	0.0556	10050.939
1470	134.9	19.8	111.6	374	0.45	266	460	5.589	0.722	1.09	433	172	0.0171	0.0902	4446.1547
1475	11.29	18.6	118	373	0.45	266	457	5.589	0.72	1.09	452.4	188.3	0.0175	0.0946	50774.377
1480	4.995	18	118	375	0.45	267	460	5.589	0.722	1.1	462.6	188.3	0.0179	0.092	110827.72
1485	6.294	17.8	117	373	0.45	266	456	5.589	0.72	1.1	466.1	187.8	0.0183	0.0912	86856.157
1490	11.8	18.4	108	378	0.45	269	468	5.589	0.727	1.1	455.8	162.8	0.0187	0.0798	44130.723
1495	7.536	18.6	103	381	0.45	271	476	5.589	0.732	1.1	452.4	151.5	0.0191	0.0742	66806.012
1500	83.52	20.8	103	381	0.45	271	475	5.589	0.732	1.11	417.8	151	0.0196	0.0799	6888.7474
1505	7.246	14.4	103	381	0.45	271	476	5.589	0.732	1.11	531.8	150	0.0200	0.0623	53472.926
1510	51.41	19.4	103	381	0.45	271	476	5.589	0.732	1.11	439.4	151	0.0204	0.0757	10336.086
2765	13.3	16.8	107	450	0.45	320	662	5.589	0.841	1.66	483.9	162	0.1244	0.0428	35627.68
2770	6.28	15.8	107	450	0.45	320	665	5.589	0.843	1.66	501.4	160	0.1248	0.0406	70681.47

During the 100ft interval, the drilling rate was fluctuating from 4 ft/hr to 13 ft/hr before the bit was pulled out of hole, where MSE reached a value of around 200,000 psi. The WOB and RPM were adjusted to enhance the ROP, and eventually the bit was pulled out to the surface as dulling rate decreases gradually till reached its minimum value at depth of 2270 ft. In addition, there is an increase in the mechanical specific energy from 35627 to 70681 psi, where dulling rate is recorded as 0.0406 at 2770 ft as shown in Table 5. The trend of the dulling rate shows a good evidence to identify the bit condition compared with MSE trend, which might be due to other reasons such as drilling in high-pressure zone.

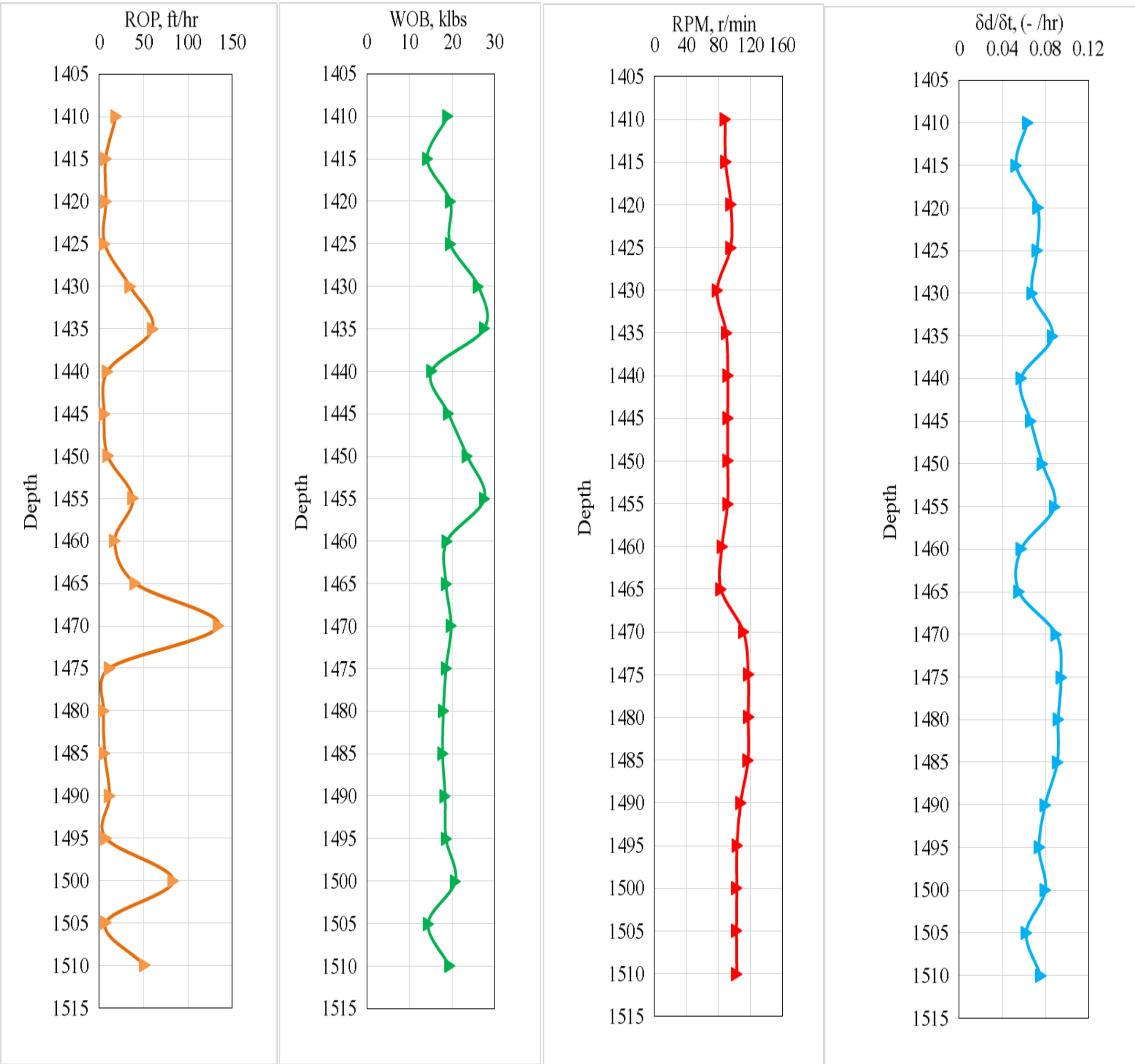
Using the data reported in the bit record as listed in Table 6, and applying the Equations 23, the function of wear can be estimated and compared to the actual wear. Both the estimated bit wear and the actual wear are plotted in Figure 14.

Table 6 Data obtained from bit record at the final depth of well 1

Depth (ft)	2772
ROP (ft/hr)	10.1
WOB (klbs)	25
RPM (r/min)	98
MW (-)	8.9
Flow (gal/min)	497.7
TFA (sq.in)	0.45
j (lb_f)	354.2
Fj (lbs)	812.1
D (-)	0.125
$\frac{\delta d}{\delta t}$ (- /hr)	0.0451
$d_{current}$ (ft)	2772
d_{in} (ft)	1264
T (hr)	149.3
$f(D)$ (-)	1.26
DG (-)	1.0

Figure 5 Graphical representation of drilling parameters and corresponding estimated dulling rate of bit run for well 1

(a) (b) (c) (d)



4.2 **Well 2**

Well 2 was drilled in field A. A $13\frac{3}{8}$ " casing was set at 222 ft, while the 12.25 drill bit was used to drill the section to the total planned depth. The bit is sharp and there was no degree of the tooth wear.

Table 7 Mud log data recorded within interval of 100 ft - Well 2

Depth (ft)	ROP (ft/hr)	WOB (klbs)	RPM (r/min)	Flow (gal/min)	TFA (sq.in)	j (lb_f)	Fj (lbs)	F1 (--)	F8 (--)	a (--)	m (--)	i (--)	D (--)	$\frac{\delta d}{\delta t}$ (- /hr)	MSE (psi)
2170	11.8	13.06	96.4	653	0.75	279.5	831.3	5.589	0.925	3.3	562.1	135.4	0.356	0.0143	27911.59
2175	11.1	10.92	97.2	653	0.75	279.5	831.3	5.589	0.925	3.3	617.6	137.1	0.357	0.0131	25131.30
2180	10.8	8.64	104.4	658.8	0.75	282.0	846.1	5.589	0.932	3.3	690.3	153.9	0.358	0.0131	21924.79
2185	10.9	10.92	103.8	623	0.75	266.6	756.7	5.589	0.889	3.3	617.6	152.4	0.359	0.0151	27269.57
2190	7.5	9.86	103.4	619.2	0.75	265.0	747.4	5.589	0.885	3.3	649.3	151.5	0.360	0.0144	35352.24
2195	8.4	12.48	102.8	619.6	0.75	265.2	748.4	5.589	0.885	3.3	576.2	150.0	0.361	0.0160	40142.49
2200	10.7	14.62	102.8	627.4	0.75	268.5	767.4	5.589	0.894	3.3	527.1	150.0	0.363	0.0173	36684.69
2205	9.8	3.9	105	637	0.75	272.6	791.0	5.589	0.906	3.3	937.0	155.3	0.363	0.0099	10945.02
2210	7.6	14.7	99.8	643.4	0.75	275.4	807.0	5.589	0.913	3.3	525.4	143.0	0.364	0.0161	50210.90
2215	10.7	10.68	100.2	645	0.75	276.1	811.0	5.589	0.915	3.3	624.5	143.9	0.365	0.0136	26102.41
2220	10.0	11.06	100.2	645	0.75	276.1	811.0	5.589	0.915	3.3	613.7	143.9	0.366	0.0138	28991.48
2225	9.2	9.42	100	645	0.75	276.1	811.0	5.589	0.915	3.3	663.4	143.5	0.366	0.0127	26731.26
2230	8.8	8.36	100.6	645	0.75	276.1	811.0	5.589	0.915	3.3	700.5	144.9	0.367	0.0121	24959.00
2235	10.2	10.9	100	645	0.75	276.1	811.0	5.589	0.915	3.3	618.2	143.5	0.368	0.0136	27940.21
2240	11.2	15.1	95	641.8	0.75	274.7	803.0	5.589	0.912	3.3	517.1	132.3	0.369	0.0150	33590.38
2245	9.7	13.22	88.4	637	0.75	272.6	791.0	5.589	0.906	3.4	558.3	118.4	0.370	0.0125	31426.06
2250	9.5	12.46	90.4	637	0.75	272.6	791.0	5.589	0.906	3.4	576.7	122.5	0.371	0.0125	31106.89
2255	8.2	8.82	91.8	637	0.75	272.6	791.0	5.589	0.906	3.4	683.9	125.4	0.372	0.0108	25990.71
2260	11.5	7.74	92	638.4	0.75	273.2	794.5	5.589	0.907	3.4	724.4	125.9	0.373	0.0102	16248.48
2265	11.4	10.82	91	637.8	0.75	273.0	793.0	5.589	0.907	3.4	620.5	123.8	0.374	0.0117	22636.39

Figure 6 MSE & ROP vs. depht in well 2

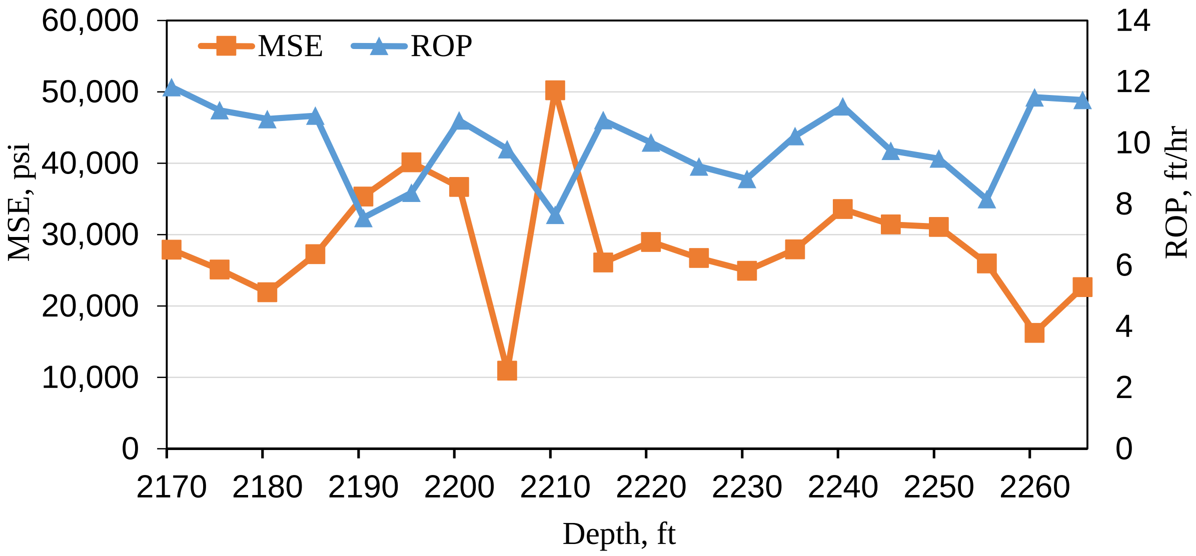


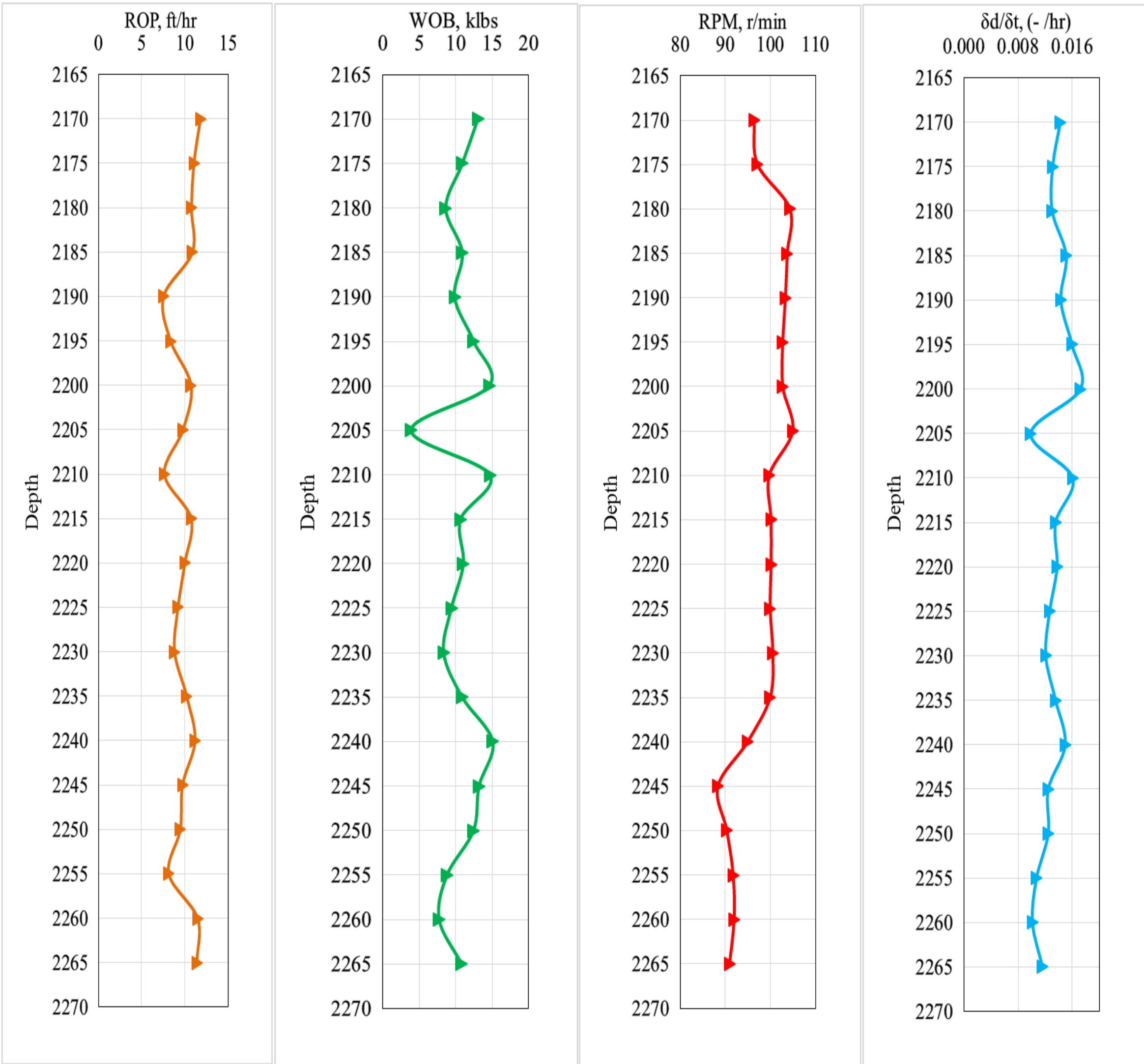
Table 8 Data obtained from bit record at the final depth of well 2

Depth (ft)	2269
ROP (ft/hr)	27.7
WOB (klbs)	20
RPM (r/min)	100
MW (-)	8.7
Flow (gal/min)	570
TFA (sq.in)	0.75
j (lb_f)	244
Fj (lbs)	626.2
D (-)	0.375
$\frac{\delta d}{\delta t}$ (- /hr)	0.0215
$d_{current}$ (ft)	2269
d_{in} (ft)	222
T (hr)	73.89
$f(D)$ (-)	3.23
DG (-)	3.0

The variation of ROP with WOB and RPM are taking from mud logging data measured at every 5 ft depth, until the bit is pulled out of hole at 2269 ft. The reason for the bit removal is not reported in the bit record. Values of the MSE are fluctuating per depth based on rate of penetration as shown in Figure 6. The MSE reacted in inverse proportion to ROP when the bit started to drill. However; during the 100 ft interval, the MSE responded haphazardly to the rate of penetration due to the possibility of having poor hole cleaning. On the other hand, the rate of dulling was dropping drastically until the end of the section at 2269 ft, which clearly reflected the condition of the bit. Towards the end of the 12.25 section, WOB was increased slightly from 7.7 to 10.8 klbs as shown in Figure 7 (b) to enhance the ROP, and as a result, the bit was damaged, as more energy was required to push the bit to drill. The bit was pulled out and the dull grade is 3 out of 8. Table 8 shows the calculation of the bit wear by applying Equation 23.

Figure 7 Graphical representation of drilling parameters and corresponding estimated dulling rate of bit run for well 2

(a) (b) (c) (d)



4.3 **Well 3**

Well 3 is located in the field A. Mud logging data for the last 100 ft interval are shown in Table 9, and the graphs are more focused on highlighting the change in ROP and MSE against the depth as shown in Figure 8.

Table 9 Mud log data recorded within interval of 100 ft - Well 3

Depth (ft)	ROP (ft/hr)	WOB (klbs)	RPM (r/min)	Flow (gal/min)	TFA (sq.in)	j (lb_f)	Fj (lbs)	F1 (--)	F8 (--)	a (--)	m (--)	i (--)	D (--)	$\frac{\delta d}{\delta t}$ (- /hr)	MSE (psi)
1605	4.33	6.4	121.8	414.4	0.543	245.00	467.75	5.589	0.727	1.72	783.33	200.37	0.118	0.037	47113.61
1610	5.88	9.6	119.4	414.2	0.543	244.85	467.16	5.589	0.727	1.72	657.57	193.41	0.118	0.042	51007.10
1615	17.77	14.8	123.2	409.7	0.543	242.17	457.02	5.589	0.720	1.73	523.31	204.51	0.119	0.056	26925.45
1620	32.93	15.2	126.4	408.5	0.543	241.49	454.44	5.589	0.718	1.73	515.04	214.21	0.119	0.060	15365.81
1625	46.30	15.6	127.6	408.5	0.543	241.49	454.44	5.589	0.718	1.73	506.98	217.93	0.120	0.062	11361.25
1630	19.98	14	126.2	408.5	0.543	241.48	454.39	5.589	0.718	1.73	540.55	213.59	0.120	0.057	23208.10
1635	16.56	15.4	124.6	408.5	0.543	241.49	454.44	5.589	0.718	1.74	510.98	208.71	0.120	0.059	30395.20
1640	8.07	9.4	124.4	408.5	0.543	241.49	454.44	5.589	0.718	1.74	664.10	208.10	0.121	0.045	37933.79
1645	5.48	14.4	118.4	413.6	0.543	244.48	465.76	5.589	0.726	1.74	531.81	190.57	0.121	0.051	81359.53
1650	4.11	11.4	115.6	416.2	0.543	246.06	471.82	5.589	0.730	1.74	604.27	182.77	0.122	0.043	83914.97
1655	6.04	15.4	117.2	416.0	0.543	245.90	471.18	5.589	0.729	1.75	510.98	187.20	0.122	0.051	78166.11
1660	44.37	17.4	123	416.1	0.543	245.97	471.46	5.589	0.729	1.75	473.11	203.91	0.122	0.060	12746.06
1665	51.72	18.6	124.2	415.3	0.543	245.53	469.78	5.589	0.728	1.75	452.43	207.50	0.123	0.064	11821.87
1670	21.18	12.4	117.6	417.7	0.543	246.94	475.18	5.589	0.732	1.75	578.19	188.31	0.123	0.045	18083.11
1675	22.10	15.2	119.2	412.5	0.543	243.83	463.29	5.589	0.724	1.76	515.04	192.84	0.124	0.053	21538.79
1680	8.74	8.2	121.4	416.4	0.543	246.16	472.18	5.589	0.730	1.76	706.46	199.19	0.124	0.039	29812.91
1685	12.70	8.6	123.2	421.1	0.543	248.93	482.86	5.589	0.737	1.76	691.69	204.51	0.125	0.041	21860.63
1690	6.82	5.6	123.6	421.2	0.543	249.02	483.22	5.589	0.737	1.76	824.75	205.70	0.125	0.034	26568.02
1695	7.85	7.6	123.2	420.7	0.543	248.70	481.98	5.589	0.736	1.77	730.03	204.51	0.125	0.039	31222.35
1700	22.05	12.4	126.4	420.4	0.543	248.51	481.25	5.589	0.736	1.77	578.19	214.21	0.125	0.051	18669.76
1705	36.60	16	126	417.4	0.543	246.76	474.50	5.589	0.731	1.76	499.13	212.98	0.125	0.059	14519.72

Figure 8 MSE & ROP vs. depht in well 3technique

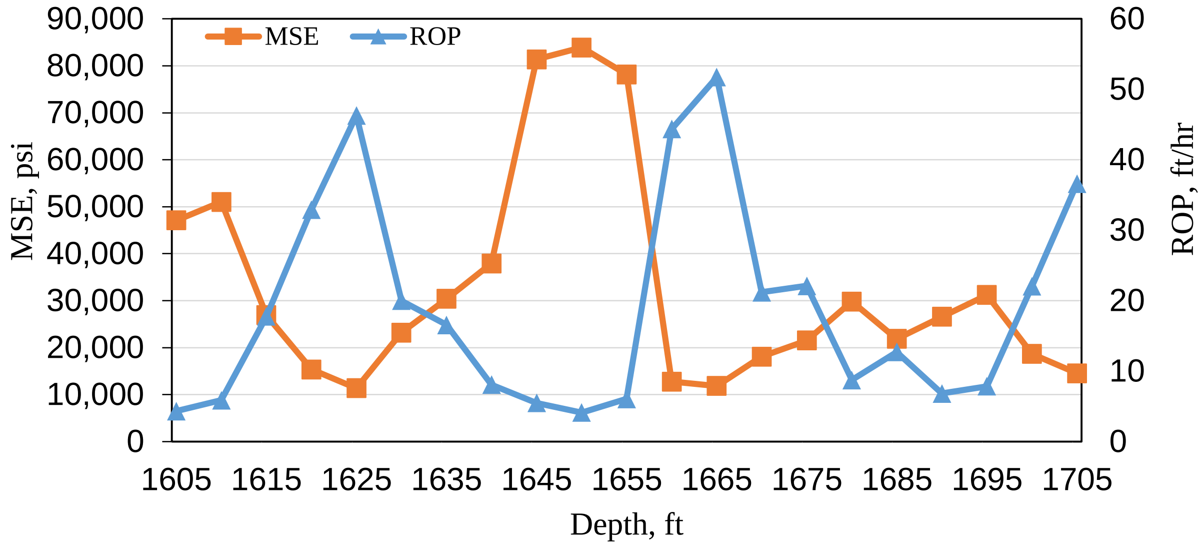


Figure 8 presents the relationship between MSE and ROP versus depth. It can be seen from Figure 9 that the penetration rate at any degree of dullness is mainly related to the weight on bit. The footage per hour decreased steadily as RPM increased. In the beginning of this interval at depth 1605 ft and after 1400ft being drilled, the ROP was recorded to be 4.3 ft/hr with only 6.4 klbs applied on the bit. This indicates that the bit was in a dull state with dulling rate of 0.037, because of an increase in the MSE as shown in Figure 9(d). The bit was not pulled out of the hole at the time due to an acceptable jump in ROP that reached 46 ft/hr. The increment of ROP was obtained immediately after applying more weight on the bit as evident in Figure 9(a).

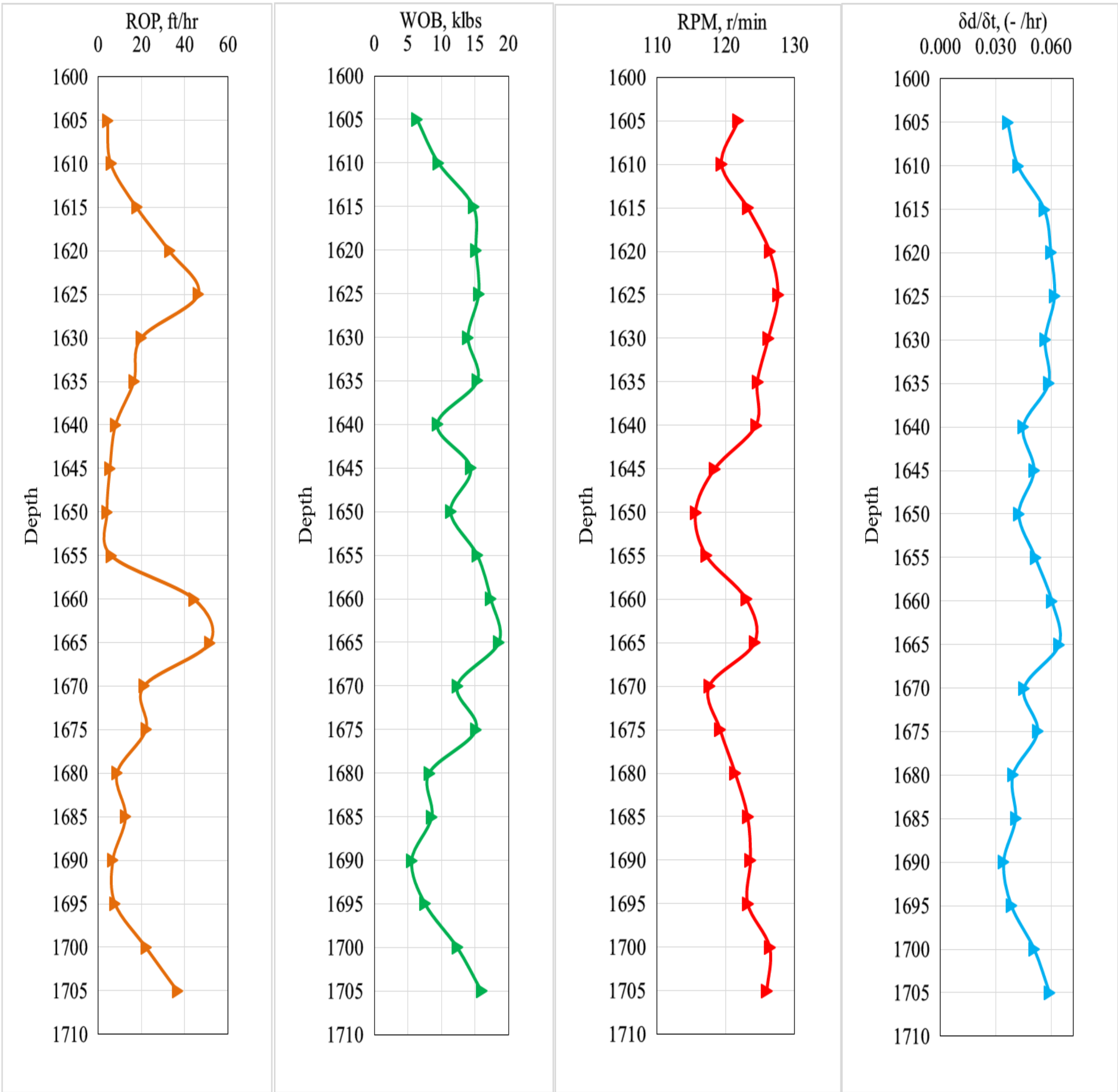
MSE once again increased gradually, with the most significant rise in MSE occurred at 1650ft as seen in Figure 8. At this point, the bit achieved only 4.11 ft/hr, which reflects the bit efficiency. To enhance the drilling rate, 38% of weight compared with the previous, was applied, and accordingly the bit efficiency was increased to about 50 ft/hr as shown in Figure 9(a). For the next 40 ft, the ROP fluctuated until the bit was pulled out of the hole for survey purpose. Once the bit is on the surface for whatever reason, the dull can be estimated by using the Equation 23 and compare it to the actual recorded dull as illustrated in Table 10.

Table 10 Data obtained from bit record at the final depth of well 3

Depth (ft)	1710
ROP (ft/hr)	16.12
WOB (klbs)	11
RPM (r/min)	100
MW (-)	8.9
Flow (gal/min)	422
TFA (sq.in)	0.543
j (lb_f)	249.4
Fj (lbs)	484.96
D (-)	0.125
$\frac{\delta d}{\delta t}$ (- /hr)	0.0320
$d_{current}$ (ft)	1710
d_{in} (ft)	202
T (hr)	93.54
$f(D)$ (-)	2.0
DG (-)	2.0

Figure 9 Graphical representation of drilling parameters and corresponding estimated dulling rate of bit run for well 3

(a) (b) (c) (d)



4.4 **Well 4**

Well 4 was drilled in field B. The 12 ¼" rock bit run at 3143 ft, drilled almost 3450 ft and achieved 32.1 ft/hr. Table 11 listed the data obtained from logs. The data was recorded at varying depth until the bit was pulled out of hole at depth of 6606 ft for the purpose of coring job.

Table 11 Mud log data recorded within interval of 100 ft - Well 4

Depth (ft)	ROP (ft/hr)	WOB (klbs)	RPM (r/min)	Flow (gal/min)	TFA (sq.in)	j (lb_f)	Fj (lbs)	F1 (--)	F8 (--)	a (--)	m (--)	i (--)	D (--)	$\frac{\delta d}{\delta t}$ (- /hr)	MSE (psi)
6505	8.86	14.8	177.2	643.2	0.94	219.65	650.81	7.017	0.779	1.77	523.31	419.12	0.243	0.083	77442.35
6510	8.49	18.2	173.8	657.0	0.94	224.36	679.03	7.017	0.799	1.77	459.17	402.06	0.243	0.088	97434.66
6515	7.78	15.2	176.8	655.4	0.94	223.81	675.73	7.017	0.797	1.77	515.04	417.09	0.243	0.082	90379.53
6520	8.72	13.6	178.4	656.8	0.94	224.29	678.62	7.017	0.799	1.77	549.54	425.27	0.244	0.078	72751.13
6525	9.16	16	176	655.4	0.94	223.81	675.73	7.017	0.797	1.77	499.13	413.04	0.244	0.083	80400.03
6530	10.41	15	177	651.2	0.94	222.38	667.10	7.017	0.791	1.77	519.15	418.11	0.245	0.082	66756.30
6535	9.85	17	175	642.6	0.94	219.44	649.59	7.017	0.779	1.78	480.33	408.03	0.245	0.088	78994.23
6540	10.74	13.4	178.6	634.6	0.94	216.71	633.52	7.017	0.767	1.78	554.13	426.30	0.245	0.080	58327.80
6545	8.52	17.8	174.2	633.0	0.94	216.16	630.33	7.017	0.765	1.78	466.06	404.04	0.246	0.091	95209.88
6550	6.69	11.2	180.8	648.8	0.94	221.56	662.19	7.017	0.787	1.78	609.76	437.77	0.246	0.073	79173.82
6555	8.40	13	179	652.2	0.94	222.72	669.15	7.017	0.792	1.78	563.53	428.37	0.246	0.077	72453.04
6560	13.29	14	178	651.2	0.94	222.38	667.10	7.017	0.791	1.78	540.55	423.22	0.247	0.079	49090.03
6565	15.48	18	174	651.2	0.94	222.38	667.10	7.017	0.791	1.78	462.60	403.05	0.247	0.088	53003.31
6570	11.78	18.8	173.2	652.8	0.94	222.92	670.38	7.017	0.793	1.78	449.11	399.11	0.247	0.090	72322.51
6575	10.59	14.2	177.8	653.4	0.94	223.13	671.61	7.017	0.794	1.78	536.15	422.19	0.248	0.079	62382.11
6580	15.36	7.6	184.4	662.2	0.94	226.13	689.82	7.017	0.806	1.78	730.03	457.03	0.248	0.062	23886.17
6585	9.29	11.4	180.6	674.6	0.94	230.37	722.34	7.017	0.828	1.79	604.27	436.72	0.248	0.070	57976.77
6590	12.47	23.6	168.4	673.8	0.94	230.10	722.23	7.017	0.828	1.79	378.58	376.04	0.249	0.096	83419.91
6595	15.93	22.8	169.2	660.4	0.94	225.52	693.79	7.017	0.809	1.79	389.28	379.82	0.249	0.096	63430.30
6600	8.01	23.4	168.6	662.2	0.94	226.13	697.58	7.017	0.811	1.79	381.22	376.98	0.250	0.097	128887.57
6605	11.36	9.6	165.6	547.2	0.94	186.86	472.09	7.017	0.647	1.79	657.57	363.06	0.250	0.068	36628.44

As it can be seen in Figure 10 and Table 11, the ROP values ranged from 6.69 to 15.9 ft/hr at 100 ft interval of this section, and that was mainly based on the changes in the WOB.

Three parameters are used to analyse the logs data, and the data obtained from the calculations, which are ROP, MSE, and dulling rate. WOB was increased from 11.4 to 23.6 klb at depth of 6590 ft as shown in Figure 11 (b), and as a result, the ROP improved dramatically to 25% of the bit performance. However, the MSE increased from 57976 psi to almost 83420 psi, which may be the cause of the bit balling. Accordingly, the WOB should be reduced and more mud need to be pumped to raise the jet impact force in order to clean the bit face. Keeping almost the same RPM and decreasing the WOB at depth of 6595 ft, the bit drilled faster as the rate of penetration is increased from 12.4 to 15.9 ft/hr as can be seen in Figure 11(a).

Reaching the depth of 6605 ft, and with such a reduction in dulling rate combined with a sudden drop in MSE as illustrated in Figure 11(d), it was extremely difficult to justify pulling it out and hence it should be left in hole. The recorded data of the bit are listed in Table 12. This information will be used to interpret bit dull condition using Equation 23, and the comparison between the actual bit wear and the estimated wear is shown in Figure 14.

Figure 10 MSE & ROP vs. depht in well 4

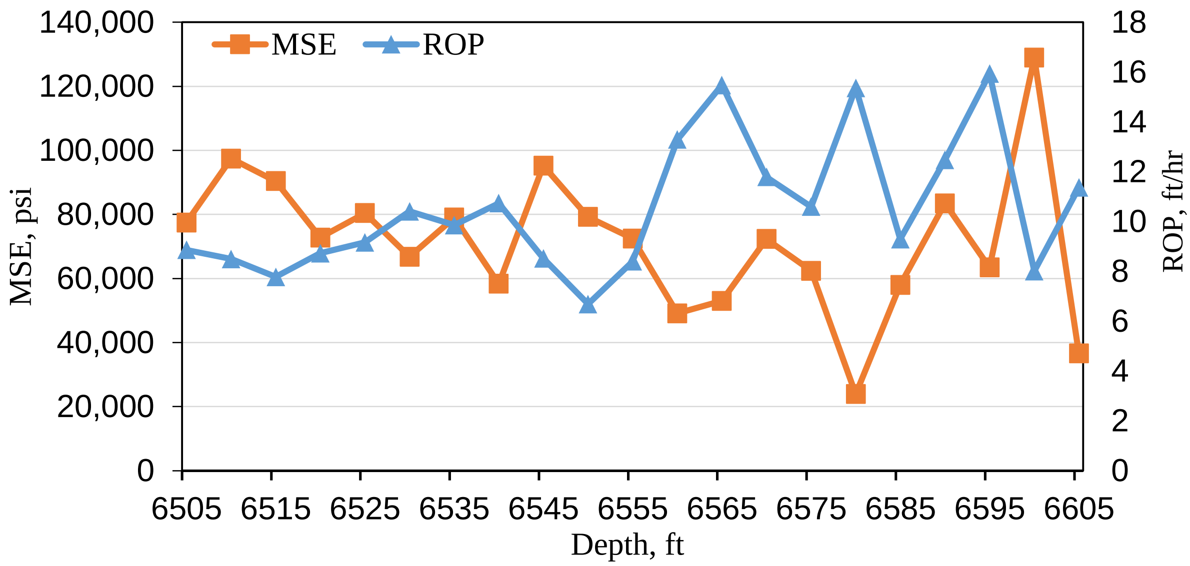
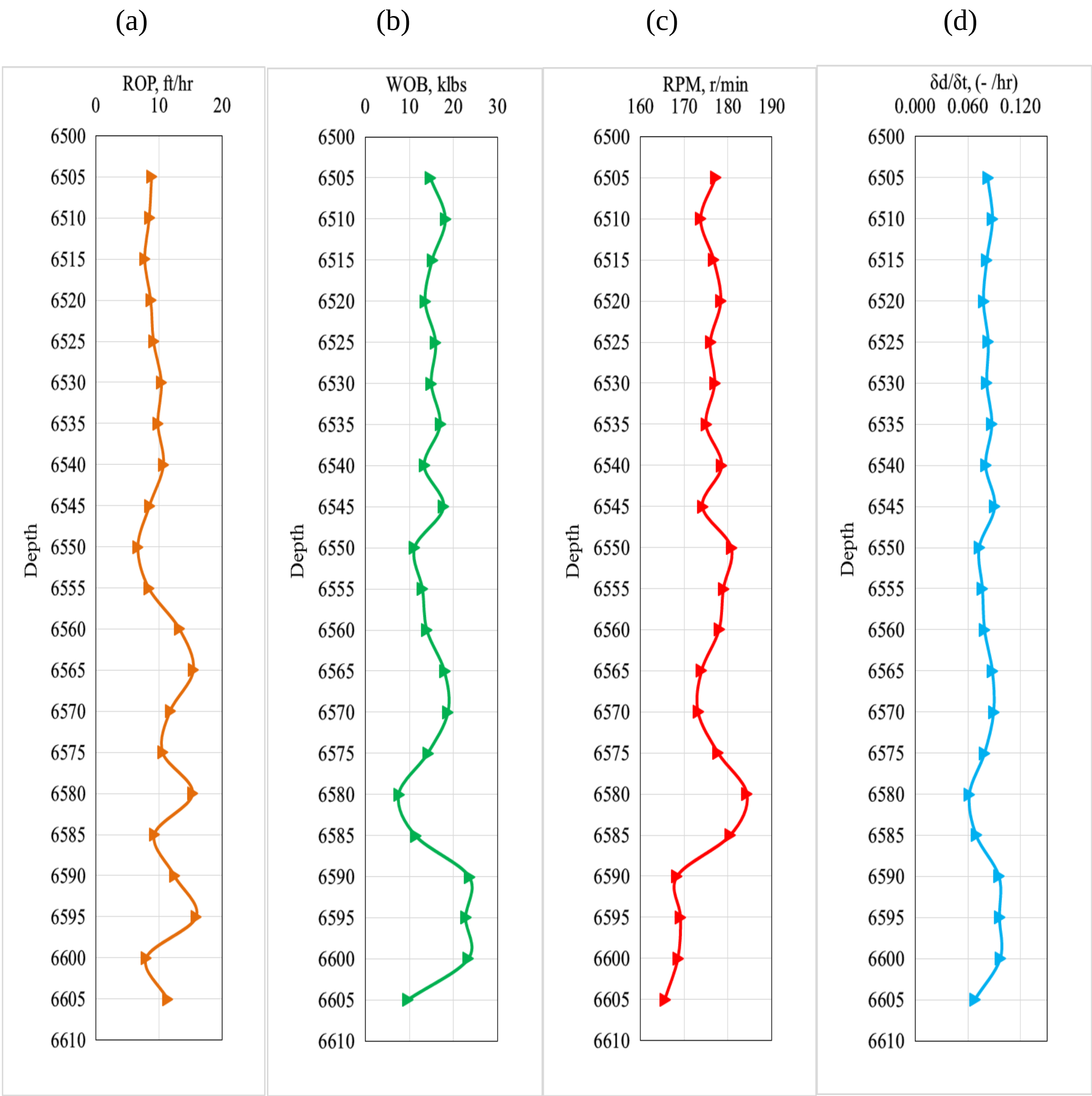


Table 12 Data obtained from bit record at the final depth of well 4

Depth (ft)	6606
ROP (ft/hr)	32.1
WOB (klbs)	20
RPM (r/min)	130
MW (-)	8.9
Flow (gal/min)	650
TFA (sq.in)	0.94
j (lb_f)	222
Fj (lbs)	664
D (-)	0.25
$\frac{\delta d}{\delta t}$ (- /hr)	0.0529
$d_{current}$ (ft)	6606
d_{in} (ft)	3143
T (hr)	107.8
$f(D)$ (-)	2.29
DG (-)	2.0

Figure 11 Graphical representation of drilling parameters and corresponding estimated dulling rate of bit run for well 4



4.5 **Well 5**

Well 5 is located in filed B. The bit used in this well was of a similar design to those ran in the previous wells. The MSE is determined along the 12 ¼" section. The benefits of monitoring real time MSE values is to help optimize the drilling operations in conjunction with other drilling parameters. This concluded that the bit continued to be efficient once the MSE exceed the rock strength. Mud logs data is shown in Table 13, and the data used to calculate other factors in order to determine bit tooth wear.

As shown in Figure 12, the efficiency level for the bit varies along the interval. The ROP was dropping linearly until it reached its minimum value 2.81 ft/hr at 4860 ft where about 375000 psi was needed for the bit to continue drilling. The reason of this may be attributed to a sign of bearing worn, due to the increment of the dulling rate. The penetration rate was increased drastically as more weight on bit was applied until it reached its peak of 12.76 ft/hr at depth of 4895 ft as shown in Figure 13 (a).

The bit was pulled out for the reason of long drilling hours, however, the average ROP was 32.9 ft/hr.

Good match between the determined bit wear and the reported bit wear in the bit records are shown in Figure 14.

Figure 12 MSE & ROP vs. depht in well 5

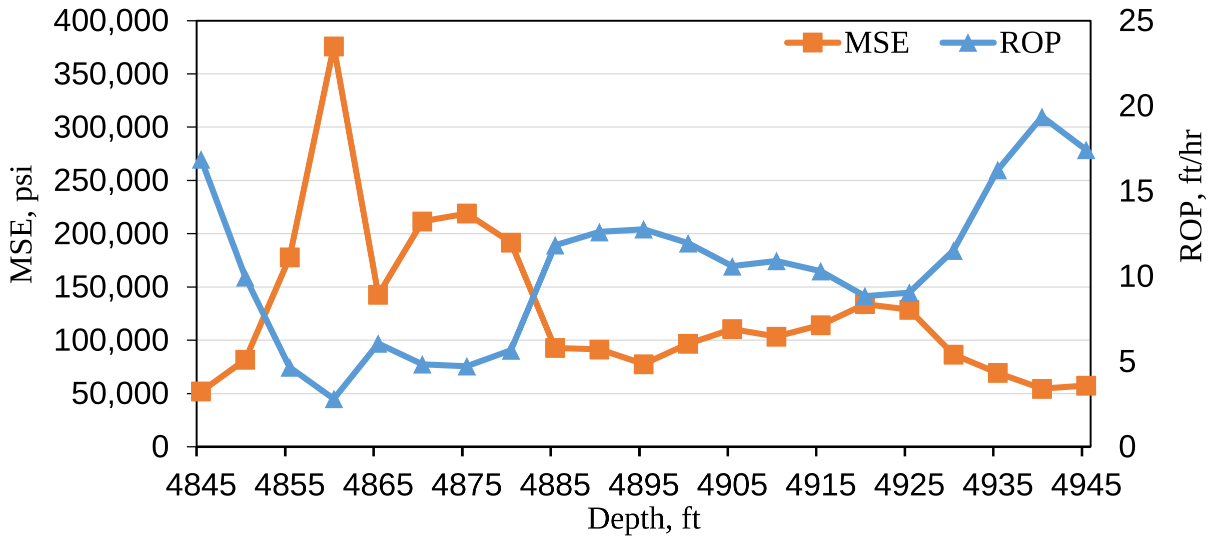


Table 13 Mud log data recorded within interval of 100 ft - Well 5

Depth (ft)	ROP (ft/hr)	WOB (klbs)	RPM (r/min)	Flow (gal/min)	TFA (sq.in)	j (lb_f)	Fj (lbs)	F1 (--)	F8 (--)	a (--)	m (--)	i (--)	D (--)	$\frac{\delta d}{\delta t}$ (- /hr)	MSE (psi)
4845	16.86	23.4	142.6	529.20	0.58	180.72	430.65	7.017	0.613	1.74	381.22	268.68	0.232	0.094	51887.03
4850	9.94	21.8	142.4	529.20	0.58	180.72	430.65	7.017	0.613	1.74	403.19	267.95	0.233	0.089	81705.83
4855	4.66	22.2	142.8	529.20	0.58	180.72	430.65	7.017	0.613	1.74	397.55	269.41	0.234	0.090	177771.00
4860	2.81	28	144.4	529.20	0.58	180.72	430.65	7.017	0.613	1.75	325.55	275.32	0.235	0.112	375743.53
4865	6.06	23.4	141.2	527.08	0.58	179.99	427.22	7.017	0.611	1.75	381.22	263.60	0.236	0.092	142667.67
4870	4.84	27.6	142	530.26	0.58	181.08	429.89	7.017	0.613	1.75	330.02	266.50	0.236	0.107	211621.58
4875	4.73	28.4	139.4	529.20	0.58	180.72	428.18	7.017	0.611	1.75	321.15	257.18	0.237	0.106	218949.37
4880	5.66	29.4	141	529.20	0.58	180.72	428.18	7.017	0.611	1.76	310.42	262.88	0.238	0.112	191683.77
4885	11.82	30.2	138.6	529.20	0.58	180.72	428.18	7.017	0.611	1.76	302.09	254.37	0.239	0.112	92706.79
4890	12.61	30.6	143.8	529.20	0.58	180.72	428.18	7.017	0.611	1.76	298.01	273.09	0.240	0.121	91427.53
4895	12.76	26	145.4	529.20	0.58	180.72	428.18	7.017	0.611	1.76	348.54	279.05	0.241	0.106	77571.29
4900	11.95	30.4	145	530.26	0.58	181.08	429.89	7.017	0.613	1.77	300.05	277.55	0.242	0.122	96620.32
4905	10.59	31.4	142.4	532.38	0.58	181.80	433.33	7.017	0.616	1.77	290.01	267.95	0.242	0.121	110532.04
4910	10.90	30.2	142.6	532.38	0.58	181.80	433.33	7.017	0.616	1.77	302.09	268.68	0.243	0.116	103420.18
4915	10.31	30.6	147	530.26	0.58	181.08	429.89	7.017	0.613	1.77	298.01	285.12	0.244	0.125	114225.81
4920	8.84	31.2	145	529.20	0.58	180.72	428.18	7.017	0.611	1.78	291.99	277.55	0.245	0.125	133930.10
4925	9.05	30.6	145.4	529.20	0.58	180.72	428.18	7.017	0.611	1.78	298.01	279.05	0.246	0.123	128718.30
4930	11.51	27	141	530.26	0.58	181.08	429.89	7.017	0.613	1.78	336.83	262.88	0.247	0.102	86581.65
4935	16.23	30.2	142	529.20	0.58	180.72	428.18	7.017	0.611	1.78	302.09	266.50	0.247	0.115	69245.60
4940	19.37	28	143.6	529.20	0.58	180.72	428.18	7.017	0.611	1.79	325.55	272.35	0.248	0.109	54456.25
4945	17.42	26.6	143.4	529.20	0.58	180.72	428.18	7.017	0.611	1.79	341.46	271.61	0.249	0.104	57412.95

Table 14 Data obtained from bit record at the final depth of well 5

Depth (ft)	4950
ROP (ft/hr)	32.9
WOB (klbs)	35
RPM (r/min)	140
MW (-)	8.6
Flow (gal/min)	531
TFA (sq.in)	0.58
j (lb_f)	181
Fj (lbs)	428
D (-)	0.25
$\frac{\delta d}{\delta t}$ (- /hr)	0.0529
$d_{current}$ (ft)	4950
d_{in} (ft)	3469
T (hr)	45
$f(D)$ (-)	2.07
DG (-)	2.0

Figure 13 Graphical representation of drilling parameters and corresponding estimated dulling rate of bit run for well 5

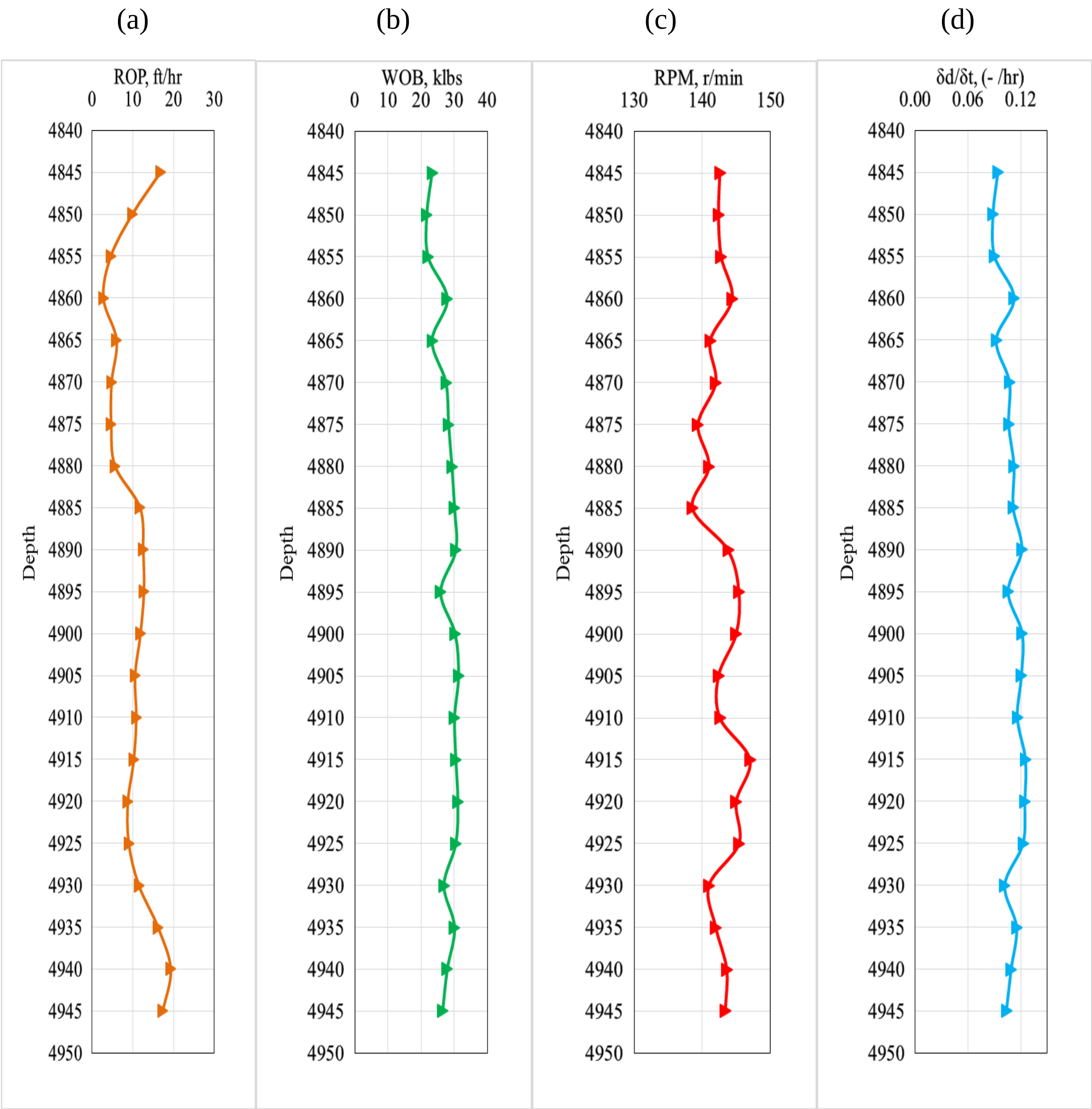
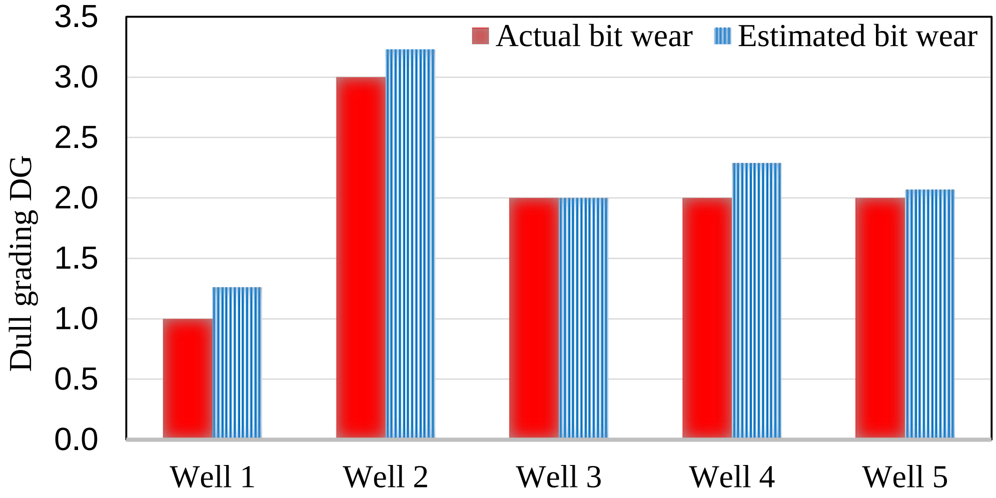


Figure 14 Comparing the actual and the estimated bit wear at the final depth for fields A & B



5 **Conclusions**

This work introduces a new method to determine the tooth bit wear by including the abrasiveness formation and mud hydraulic. The derived equation to estimate the bit wear is based on the dulling rate by combining ROP model with the modified theory of variable weight and rotary speed for rock bits using the actual field data. Both the bit wear as a function of dulling rate, and the abrasiveness formation are determined using the new equations.

The MSE does not reliably reflect the bit condition while drilling as high values of MSE may be obtained due to bit balling or drilling in high pressure zone. On the other hand, and based on the results, dulling rate is proven to be a good indicator for predicting the bit wear condition in real time. This is in contrast with what was obtainable in the literature.

gPROMS simulation software used to calculate the BY rate of penetration model coefficients. The calculated coefficients fit within the proposed bounds and used to estimate the bit tooth wear. The estimated bit tooth wear for most of the wells exceeds the actual bit wear because of the additional feet that the bit drilled before it penetrates to the candidate formation. Good agreement is obtained because of the different 12.25-inch bit sections between the reported and estimated bit wear using the real field data. Future research can focus on the different types of drilling bits (e.g. PDC bits), and different type of formations (e.g. sandstone).

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